VISIT…

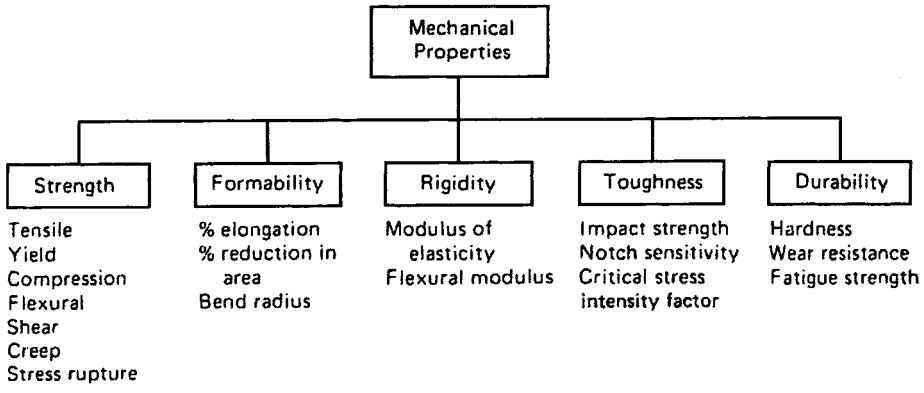

Fig. 5-4 General guides to mechanical property tests.

range will produce a lower shrinkage. (5) A longer cycle time, above the required solidification point, will partially conform the product closer to the mold dimensions, thereby bringing about lower shrinkage. (6) Openings in a product (holes and core shapes) will somewhat interfere with shrinkage in the cavity and thus will bring about lower and varying shrinkages than would be the case in a product without openings. (7) Larger feeding gates to the product will cause lower shrinkage permitting higher pressure buildup in the cavity. (8) Materials that are crystalline have dual shrinkage so they are higher in the direction of material flow and lower perpendicular to it. In a symmetrical part; when center gated, the shrinkage will average out and be reasonably uniform. (9) Most TPs attain their full shrinkage after 24 hours, but there are some which may take weeks to stabilize their dimensions fully (manufacturer of the material usually indicates whether there is a delayed shrinkage effect present). (10) Glass fiber-reinforced or otherwise filled TPs have considerably lower shrinkages than the basic plastic.

The TS plastic compression-molded products will have a higher shrinkage when: (1) cavity pressure is on the low side, (2) when mold temperature is on the high side, (3) when cures are shorter, (4) when products are thicker, (5) when a material is soft flowing (highly plasticized), (6) when a material is preheated at relatively low heat, and/or (7) when a high moisture content is present in the raw material.

Mechanical Property

As summarized in Fig. 5-4 mechanical properties encompass different behaviors.

Tensile Property

It should be recognized that tensile properties would most likely vary with a change of speed of the pulling jaws and with variation in the atmospheric conditions. Figure 2-14 shows the variation in a stress-strain curve when the speed of testing is altered; also shown are the effects of temperature changes on the stress-strain curves. When the speed of pulling force is increased, the material reacts like brittle material; when the temperature is increased, the material reacts like ductile material.

The tensile data show the stress necessary to pull the specimen apart and the elongation prior to breaking. A moderate elongation (about 6%) of a test specimen generally implies that the material is capable of absorbing rapid impact and shock. The area under the stress-strain curve is indicative of overall toughness except for reinforced plastics (Fig. 2-9). A material of very high strength, high rigidity, and little elongation would tend to be brittle in service. For applications where almost rubbery elasticity is desirable, a high ultimate (over 100%) elongation is an asset.

The tensile test and the calculated property data from it provide a most valuable source of

information for the designer in determining product dimensions. The important consideration is that use conditions compare reasonably closely to the test conditions as far as speed of load, temperature, and moisture are concerned. Should use conditions differ appreciably, a test should be requested for data that are comparable to service requirements, which would thereby ensure that applicational needs will be based on more exacting data. The test is relatively inexpensive, and, where critical uses are encountered, it will eliminate interpolation and guessing. The tensile data are also useful for comparing various materials in this property. It is to be noted that tensile data should only be applied to short-term stress conditions, such as operating a switch or shifting a clutch gear, etc.

The yield point is the first point on the stress-strain curve at which an increase in strain occurs without an increase in stress. The stress at which a material exhibits a special limiting deviation from the proportionality of stress-to-strain is the yield strength. A material whose stress-strain curve exhibits points of zero slope may be considered to have a yield point such as described in Fig. 2-11. The data sheets usually omit the yield strength when there is a zero slope point on the stress-strain curve in the yield region. In reinforced plastic materials, the values of the yield strength and the tensile strength are very close to each other.

The important tensile modulus (modulus of elasticity) is another property derived from the stress-strain curve. The speed of testing, unless otherwise indicated is 0.2 in./min, with the exception of molded or laminated TS materials in which the speed is 0.05 in./min. The tensile modulus is the ratio of stress to corresponding strain below the proportional limit of a material and is expressed in psi (pounds per square inch) or MPa (mega-Pascal) (Fig. 2-7).

The proportional limit is the greatest stress that a material is capable of sustaining without any deviation of the proportionality law. It is located on the stress-strain curve below the elastic limit. The elastic limit is the greatest stress that a material is capable of sustaining without any permanent strain remaining upon complete release of the stress.

For materials that deviate from the proportionality law even well below the elastic limit, the slope of the tangent to the stress-strain curve at a low stress level is taken as the tensile modulus. When the stress-strain curve displays no proportionality at any stress level, the secant modulus is employed instead of the tensile modulus (Fig. 2-2). The secant modulus is the ratio of stress to corresponding strain, usually at 1% strain or 85% from the initial tangent modulus.

The tensile modulus is an important property that provides the designer with information for a comparative evaluation of plastic material and also provides a basis for predicting the short-term behavior of a loaded product. Care must be used in applying the tensile modulus data to short-term loads to be sure that the conditions of the test are comparable to those in use. The longer-term modulus is treated under the creep test (Chapter 2).

The tensile data can be applied to the design of short-term (such as 1 or 2 hour duration) or intermittent loads in a product provided the use temperature, the humidity, and the speed of the load are within 10% of the test conditions outlined under the procedure. The intermittent specification merely indicates that there be sufficient time for strain recovery after the load has been removed.

The next step is to determine an allowable working stress. This is done by using a safety factor usually of $1\frac{1}{2}$ to $2\frac{1}{2}$ on the yield strength or tensile strength. If the type of stress is clearly defined, the $1\frac{1}{2}$ factor is adequate; otherwise, it should be higher (Chapter 2, **Safety Factor**).

The final step is to calculate the elongation that the product would experience under the selected allowable working stress to see if such an elongation would permit the proper functioning of the product. The elongation could conceivably become the limiting component, and the working stress can be calculated from:

$$\text{Modulus} = \text{stress/strain} = E \qquad (5\text{-}3)$$

If product use conditions vary appreciably from those of the standard test, a stress-strain curve, derived using the procedure of anticipated requirement, should be requested and appropriate data developed.

Flexural Property

These properties apply to products subjected to bending, and, since many plastic products are involved in uses where bending stresses are generated, this deserves close attention, especially in view of the viscoelastic nature of the materials.

It should be noted that test information would vary with specimen thickness, temperature, atmospheric conditions, and different speed of straining force. This test is made at 73.4°F (23°C) and 50% relative humidity. For brittle materials (those that will break below a 5% strain) the thickness, span, and width of the specimen and the speed of crosshead movement are varied to bring about a rate of strain of 0.01 in./in./min. The appropriate specimen size are provided in the test specification.

The flexural strength is the maximum stress that a material sustains at the moment of break. For materials that do not fail, the stress that corresponds to a strain of 5% is frequently reported as the flexural strength (Fig. 2-15).

As a matter of interest it should be stated that in this test the force of bending and associated amount of deflection is recorded. A formula gives the relationship between deflection and strain:

The flexural yield strength is determined from the calculated data of load-deflection curves that show a point where the load does not increase with an increase in deflection.

The flexural modulus is the ratio, within the elastic limit, of stress to corresponding strain. It is calculated by drawing a tangent to the steepest initial straight-line portion of the load-deflection curve and using an appropriate formula.

In many plastic materials, as is the case with metals, when performing the flexural tests, increasing the speed of deflecting force makes the specimen appear more brittle and increasing the temperature makes it appear more ductile. This is the same relationship as in tensile testing.

When materials are evaluated against each other, the flexural data of those that break in the test cannot be compared unless the conditions of the test and the specimen dimensions are identical. For those materials (most TPs) whose flexural properties are calculated at 5% strain, the test conditions and the specimen are standardized, and the data can be analyzed for relative preference. For design purposes, the flexural properties are used in the same way as the tensile properties. Thus, the allowable working stress, limits of elongation, etc. are treated in the same manner as are the tensile properties.

Compressive Property

The compressive data are of limited design value. They can be used for comparative material evaluation and design purposes if the conditions of the test approximate those of the application. The data are of definite value for materials that fail in the compressive test by a shattering fracture. On the other hand, for those that do not fail in this manner, the compressive information is arbitrary and is determined by selecting a point of compressive deformation at which it is considered that a complete failure of the material has taken place. About 10% of deformation are viewed in most cases as maximum.

The test can provide compressive stress, compressive yield, and modulus. Many plastics do not show a true compressive modulus of elasticity. When loaded in compression, they display a deformation, but show almost no elastic portion on a stress-strain curve; those types of materials should be compressed with light loads. The data are derived in the same manner as in the tensile test. Compression test specimen usually requires careful edge loading of the test specimens otherwise the edges tend to flour/spread out resulting in inacturate test result readings (2–19).

Shear Strength

The specimen is mounted in a punch-type shear fixture, and the punch (1 in. diameter) is pushed down at a rate of 0.05 in./min until the moving portion of the sample clears the stationary portion. Shear strength is calculated as the force per area sheared. Shear strength is particularly important in film and sheet products where failures from this type of load may occur (Fig. 2-21). This property can be used for comparison with other materials and for determination of the forces needed for punching openings (holes, etc.).

Izod Impact

The popular Izod impact tester can use different size specimens depending on the type of plastic and their method of fabrication. The specimen is usually 1/8 in. × ½ in. × 2 in.; other sizes are also used. Specimens can be notched or unnotched. A notch is cut in a specified manner on the narrow face of the specimen. The sample is clamped in the base of a pendulum testing machine so that it is cantilevered upward with the notch facing the direction of impact. The pendulum is released, and the force expended in breaking the sample is calculated from the height the pendulum reaches on the follow-through. The speed of the pendulum at impact is controlled.

The impact test, with its usual notch, indicates the energy required to break notched specimens under standard conditions. It is calculated as foot-pounds per inch (J/m) of notch and is usually calculated on the basis of 1 in. wide specimen, although the specimen may be thinner in the lateral direction.

The Izod value is useful in comparing various types of grades of a plastic within the same material family. In comparing one plastic with another, however, the Izod impact test should not be considered a reliable indicator of overall toughness or impact strength. Some materials are notch-sensitive and develop greater concentrations of stress from the notching operation. It should be noted that the notch serves not only to concentrate the stress, but also to present plastic deformation during impact.

The Izod impact test may indicate the need to avoid inside sharp corners on parts made of such materials. For example, nylon and acetal-type plastics, which in molded products are among the toughest materials, are notch-sensitive and register relatively low values on the notched Izod impact test.

Tensile Impact

Small and long specimens of tensile bar shape specimens have their major change in dimensions in the necked-down section. The specimen is mounted between a pendulum head and crosshead clamp on the pendulum of an impact tester. The pendulum is released and it swings past a fixed anvil that halts the crosshead clamp. The pendulum head continues forward, carrying the forward portion of the ruptured specimen. The energy loss (tensile impact energy) is recorded, as well as whether the failure appeared to be of a brittle or ductile type.

This test has possible advantages over the notched Izod test. The notch sensitivity factor is eliminated, and energy is not used in pushing aside the broken portion of the specimen. The test results are recorded in ft-lb/in.^{2} (kJ/m^2). This allows for minor variations in dimensions of the minimum in cross-section area.

Two specimens are used, S and L (short and long), so that the effect of elongation on the result can be observed. A ductile failure (best observed on the L specimen) results in a higher elongation and, consequently, in a higher total energy absorption than a brittle failure (best observed on the S specimen) in any specific material. The energy for specimen fracture is a function of the force times the distance it travels. Thus two materials showing the same energy values in the tensile impact test (all elements of the test being the same) could consist of two different factors, such as a small force and a large elongation compared to a large force and a small elongation.

If one is to consider the application of these data to a design, the size of the force and its rate of application would have to be obtained and compared with the design requirement. The breakdown of energy into components

of force and speed becomes possible by the addition of electronic instrumentation to the testing apparatus, thus enabling the supplier of the material to furnish additional information for material selection.

Impact Strength

The data from the Izod and tensile impact tests can be comparatively evaluated especially when experience has been acquired with any one type of material (Table 5-2). One should keep in mind their individual limitations. Impact resistance is a significant characteristic of a material in many product designs. Associated with impact resistance is the term material toughness. Neither one can be measured in a way that is meaningful to the designer. Per ASTM test procedures test specimens can be of different thicknesses. With certain plastics from different manufacturers the impact strength test result for one thickness can be higher than the other using a different thickness. However in actual service, products from these materials can show the tougher material to have the lower impact strength result; this is a rare situation (Chapter 7, **SELECTING PLASTIC, Property Category, *Impact***).

The term impact implies a very high speed of the acting force, whereas toughness is not related to any specific speed. Since the two terms are used in conjunction with each other in describing resistance to impact, it appears desirable to correlate those readily obtainable properties that would reflect on speed of impact and toughness.

At a 73.4°F (23°C) test temperature and a (ASTM) speed of acting force listed in each test category, the following results prevail: (1) a high modulus and high Izod points to a very tough material, (2) a high modulus and low Izod points to a brittle material, and (3) a low modulus and high Izod points to a flexible and ductile material.

When use conditions differ from those applied to data sheet tests, certain comparative evaluation can be made. Selecting an established high impact plastic such as polycarbonate as the standard, a tensile test would be made on this material at use speeds of striking force and end use environmental conditions. This provides a modulus and stress-strain curve. The same kind of test would be made on the materials being evaluated.

The area under a tensile stress-strain curve is a measure of toughness. It thus becomes possible to compare the modulus and areas under the curve and thereby estimate impact strength as a percentage of the standard. The notch sensitivity factor is eliminated and a judgment element is introduced that can prove accurate if the information is diligently analyzed. Where critical design areas involving safety to humans or protecting valuable devices are concerned, the simulation of end use with full size prototype products (including extremes of conditions) is the most desirable way to test selected materials.

There are other types of impact tests for shock loading where energy is required to cause complete failure is reported. Each has their specific behaviors that can be related to specific product performance requirements. Tests include ball burst, ball or falling dart using different weights and heights, bag drop, bullet-type instantaneous impact, Charpy, dart drop, Mullen burst, tear resistance, and tub (2).

Hardness

Hardness basically is the resistance to indentation as measured under specific conditions such as depth of indentation, load applied, and time period. Different tests relate to different hardness behaviors of plastics. They include Barcol, Brinell, durometer, Knoop, Mohs, Rockwell, Shore, and Vicat (2).

Hardness is closely related to strength, stiffness, scratch resistance, wear resistance, and brittleness. The opposite characteristic, softness, is associated with ductility. There are different kinds of hardness that measure a number of different properties (Fig. 5-5). The usual hardness tests are listed in three categories: (a) to measure the resistance of a material to indentation by an indentor; some measure indentation with the load applied, some the residual indentation after it is removed, such as tests using Brinell hardness,

Table 5-2 Room temperature impact resistance data for several plastics

Generic Material Type	Trademark	Grade	Izod Impact Energy for 0.318 cm (0.125 in.) thick, Notched Specimens, J/m	Tensile-impact Short Specimens, kJ/m^2	Energy Long Specimens, kJ/m^2
ABS	Cycolac	DH	235	99–131[a]	
		GSM	374	102–115[a]	
		KJB	214	95	
		L	400	100–120[a]	
Acetal copolymer	Celcon	M25	85		190
		M90	75		150
Acetal homopolymer	Delrin	100	123		350
		500	74.7		200
		900	69.4		150
Acrylic	Plexiglas	V052/045	21[b]		
		MI-7	32[c]		
		DR	64[b]		
Nylon (DAM) (0.2% moisture)	Zytel	101	53	157	504
		ST 801	907		588
		158 L	53	153	611
		211	80		525
Nylon (50% RH) (2.5% moisture)	Zytel	101	112	231	1470
		ST 801	1068		1155
		158 L	75	218	945
Phenolic	Durez	29053[d]	19		
		152[d]	17		
		18441[d]	14		
Polycarbonate	Lexan	141	640–850	473–631	
		940	640	526	
Polyethylene	Dow	08064N	53		88
		10062N	48		105
		04052N	80		140
		08035N	130		81
Phenylene ether copolymer	Prevex	PQA	267	113[a]	
		VKA	293	86[a]	
Polypropylene	Pro-fax	6523	42.7		
		7523	133.5		
		8523	379		
Polystyrene	Fostarene	50	21		
	Hostyren	360	54		
		760	97		
		840	161		
Polysulfone	Udel	P-1700	69	341	
		P-1710	69	421	
		P-1270	69	336	

[a] 0.159 cm ($\frac{1}{16}$ in.) thick specimens.
[b] Molded notch.
[c] 0.635 cm (0.250 in.) thick specimen with molded notch.
[d] Injection-molded specimens.

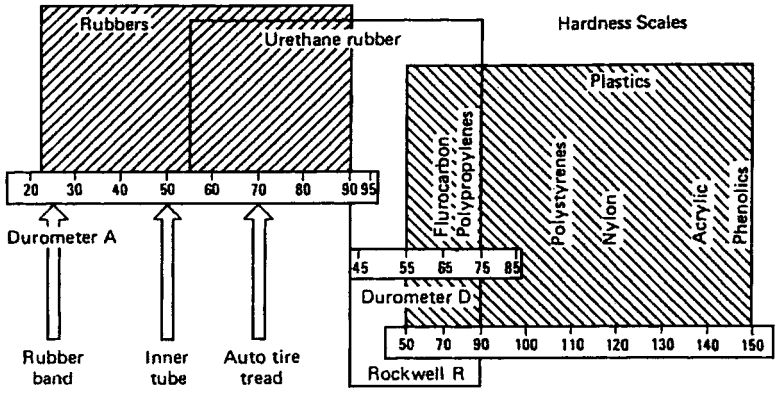

Fig. 5-5 Hardness of different materials using different test methods.

Vickers and Knoop indentors, Barcol hardness, and Shore durometers (2); (b) to measure the resistance of a material to scratching by another material or by a sharp point, such as the Bierbaum hardness or scratch-resistance test and the Moh one for hardness; and (c) to measure rebound efficiency or resilience, such as the various Rockwell hardness tests. The various tests provide different behavior characteristics for plastics, as described by different ASTM standards such as D 785. The ASTM and other sources provide different degrees of comparison for some of these tests.

Some ductile plastics, such as PC and ABS, can be fabricated like metals with punching and cold-forming techniques. These processing techniques are analogous to the hardness tests in that a rigid "indentor" is pressed into a sheet of a less-rigid plastic.

Durometer hardness An arbitrary numerical value that measures the resistance to intention of a blunt indenter point of the durometer. The higher the number, the greater indention hardness.

Barcol hardness Also called Barcol impresser. It is a measure of the hardness of a plastic, that includes laminate or reinforced plastic, using a Barber Coleman spring loaded indenter. Gives a direct reading on a 0 to 100 scale; higher number indicates greater hardness. This test is often used to measure the degree of cure for plastics, particularly TS plastics.

Brinell hardness A common test used to determine the hardness of a material by indentation of a specimen. Pressing a hardened steel ball generally 10 mm diameter down on a specimen carries out the test, and the diameter of the subsequent impression formed provides a basis for calculating hardness.

Knoop hardness It is a measure of hardness is measured by a calibrated machine that forces a rhomb-shape, pyramidal diamond indenter having specified edge angles under specific small loading conditions into the surface of the test material; the long diagonal in the material is measured after removal of the load.

Mohs hardness It is a measure of the scratch resistance of a material. The higher the number, the greater scratch resistance with number 10 being termed diamond.

Rockwell hardness Sheets or plaques at least 0.25 in. thick are used. This thickness may be built up of thinner pieces, if necessary. A steel ball under a minor load is applied to the surface of the specimen. This indents the specimen slightly and assures good contact. The gauge is then set at zero. Basically the major (higher) load is applied for 15 seconds and removed, leaving the minor load still applied. The indentation remaining after 15 seconds is read directly off the testing equipment dial.

The size of the balls used and loadings vary, and values obtained with one set cannot

be correlated with values from another set. Rockwell hardness can differentiate the relative hardness of different types of a given plastic; but, since elastic recovery is involved as well as hardness, it is not valid to compare the hardness of various types of plastic entirely on the basis of this test.

Hardness usually implies resistance to abrasion, wear, or indentation (penetration). In plastics it only means resistance to indentation. The scales range from; (1) "R" with a major load of 60 kg; indenter of 0.5 in., (2) "L" with a major load of 60 kg; indenter of 0.25 in., (3) "M" with a major load of 100 kg; indenter of 0.25 in., (4) "E" with a major load of 100 kg; indenter of 0.125 in., and (5) "K" with a major load of 150 kg; indenter of 0.125 in.

The hardness is of limited value to the designer, but can be of some value when comparing these data between materials.

Scleroscope hardness It is a dynamic indentation hardness test using a calibrated instrument that drops a diamond-tipped hammer from a fixed height onto the surface of the material being tested.

Shore hardness It is the indentation hardness of a material as determined by the depth of an indentation made with an indenter of the Shore type durometer. The scale reading on this durometer is from zero (corresponding to 0.100 in. depth) to 100 for zero depth. The Shore A indenter has a sharp point, is spring-loaded, and is used for the softer plastics. The Shore B indenter has a blunt point, is spring-loaded at a higher value, and is used for harder plastics.

Vicat hardness It is a determination of the softening point for TPs that have no definite melting point. The softening point is taken the temperature at which the specimen is usually penetrated to a depth of 1 mm^2 (0.0015 in^2) circular or square cross section, under a 1,000 g load.

Deformation Under Load

The specimen is a small cube, either solid or composite. It is placed between the anvils of the testing machine, and loaded at 1000, 2000, or 4000 psi. The gauge is read 10 s after loading, and again 24 h later. The deflection is recorded in mils. Calculation is made after the specimen is removed from the testing machine. By dividing the change in height by the original height and multiplying by 100, the percentage deformation is calculated. This test may be run at different temperatures.

This test on rigid plastics indicates their ability to withstand continuous short-term compression without yielding and loosening when fastened as in insulators or other assemblies by bolts, rivets, etc. It does not indicate the creep resistance of a particular plastic for long periods of time. It is also a measure of rigidity at service temperatures and can be used as identification for procurement. Data should indicate stress level and the temperature of the test.

Fatigue Strength

The fatigue strength is defined as that stress level at which the test specimen will sustain "N" cycles prior to failure. The data are generated on a machine that runs at 1800 cycles per minute. This test is of value to material manufacturers in determining consistency of their product (Chapter 2).

Long-Term Stress Relaxation/Creep

This review concerns the long-term behavior of plastics when exposed to conditions that include continuous stresses, environment, excessive heat, abrasion, and continuous contact with liquids. This subject has been reviewed in Chapter 2 (**LONG-TERM LOAD BEHAVIOR**) but since it is a very important subject the review is continuing. Tests such as those outlined by ASTM D 2990 that describe in detail the specimen preparations and testing procedure are intended to produce consistency in observations and records by various manufacturers, so that they can be correlated to provide meaningful information to product designers.

The procedure under this heading is intended as a recommendation for uniformity

of making setup conditions for the test, as well as recording the resulting data. The reason for this action is the time consuming nature of the test (many years duration), which does not lend itself to routine testing. The test specimen can be round, square, or rectangular and manufactured in any suitable manner meeting certain dimensions. The test is conducted under controlled temperature and atmospheric conditions.

The requirements for consistent results are outlined in detail as far as accuracy of time interval, of readings, etc., in the procedure. Each report of test results should indicate the exact grade of material and its supplier, the specimen's method of manufacture, its original dimensions, type of test (tension, compression, or flexure), temperature of test, stress level, and interval of readings.

When a load is initially applied to a specimen, there is an instantaneous strain or elongation. Subsequent to this, there is the time-dependent part of the strain (creep), which results from the continuation of the constant stress at a constant temperature. In terms of design, creep means changing dimensions and deterioration of product strength when the product is subjected to a steady load over a prolonged period of time.

All the mechanical properties described in tests for the conventional data sheet properties represented values of short-term application of forces, and, in most cases, the data obtained from such tests are used for comparative evaluation or as controlling specifications for quality determination of materials along with short-duration and intermittent-use design requirements.

The visualization of the reaction to a load by the dual component interpretation of a material is valuable to the understanding of the creep process, but meaningless for design purposes. For this reason, the designer is interested in actual deformation or part failure over a specific time span. This means making observations of the amount of strain at certain time intervals which will make it possible to construct curves that could be extrapolated to longer time periods. The initial readings are 1, 2, 3, 5, 7, 10, and 20 h, followed by readings every 24 h up to 500 h and then readings every 48 h up to 1000 h (Chapter 2).

The time segment of the creep test is common to all materials, i.e., strains are recorded until the specimen ruptures or the specimen is no longer useful because of yielding. In either case, a point of failure of the test specimen has been reached.

The stress levels and the temperature of the test for a material is determined by the manufacturer. The guiding determinants are the continuous allowable working stress at room temperature and the continuous allowable working stress at temperatures of potential applications.

The strain readings of a creep test can be more convenient to a designer if they are presented as a creep modulus. In a viscoelastic material, strain continues to increase with time while the stress level remains constant. Since the modulus equals stress divided by strain, we have the appearance of a changing modulus.

The creep modulus, also known as apparent modulus or viscous modulus when graphed on log-log paper, is normally a straight line and lends itself to extrapolation for longer periods of time. The apparent modulus should be differentiated from the modulus given in the data sheets, because the latter is an instantaneous value derived from the testing machine.

The method of obtaining creep data and their presentation have been described; however, their application is limited to the exact same material, temperature use, stress level, atmospheric conditions, and type of test (tensile, compression, flexure) with a tolerance of ±10%. Only rarely do product requirement conditions coincide with those of the test or, for that matter, are creep data available for all grades of material that may be selected by a designer. In those cases a creep test of relatively short duration such as 1000 h can be instigated, and the information can be extrapolated to the long-term needs. It should be noted that reinforced thermoplastics and thermosets display much higher resistance to creep (Chapter 2).

Creep information is not as readily available as short-term property data sheets are. From a designer's viewpoint, it is important to have creep data available for products subjected to a constant load for

prolonged periods of time. The cost of performing or obtaining the test in comparison with other expenditures related to product design would be insignificant when considering the element of safety and confidence it would provide. Furthermore, the proving of product performance could be carried out with a higher degree of favorable expectations as far as a plastic material is concerned. Progressive material manufacturers can be expected to supply the needed creep and stress-strain data under specified use conditions when requested by designer; but, if that is not the case, other means should be utilized to obtain required information.

In conclusion regarding creep testing, it can be stated that creep data and a stress-strain diagram indicate whether plain plastic properties can lead to practical product dimensions or whether a RP has to be substituted to keep the design within the desired proportions. For long-term product use under continuous load, plastic materials have to consider creep with much greater care than would be the case with metals.

Summation

Throughout this book all the different types of mechanical properties are presented and reviewed. These mechanical properties include a tremendous range of different types that can usually be characterized by their stiffness, strength, and toughness.

Stiffness The same factors that influence thermal expansion dictate the stiffness of plastics. Thus in a TS the degree of cross-linking and amount of overall flexibility are important. As an example, in a TP its crystallinity and secondary bond's strength control its stiffness.

Strength The subject of strength is much more complex than stiffness, since so many different types exist such as short or long term, static or dynamic, and torsion or impact strengths. Some strength aspects are interrelated with those of toughness. This section reviews certain simplified concepts of strength that are important influences on strength based on long and short term exposure.

The crystallinity of TPs is important for their short term yield strength. Unless the crystallinity is impeded, increased molecular weight generally also increases the yield strength. However, the cross-linking of TSs increases their yield strength substantially but has an adverse effect upon toughness.

Long term rupture strengths in TPs are increased much more readily by increasing the secondary bonds' strength and crystallinity than by increasing the primary bond strength. Fatigue strength is similarly influenced, and all factors that influence thermal dimensional stability also affect fatigue strength. This is a result of the substantial heating that is often encountered with fatigue, particularly in TPs.

Toughness The subject of toughness is usually the most complex factor to define and understand. Tough plastics are usually described as ones having a high elongation to failure or ones in which a lot of energy must be expended to produce failure. For high toughness a plastic needs both the ability to withstand load and the ability to elongate substantially without failing except in the case of reinforced TSs that are tough, which may have high strengths with low elongation.

It may appear that factors contributing to high stiffness are required, but this is not true, because there is an inverse relationship between flaw sensitivity and toughness: the higher the stiffness and the yield strength of a TP, the more flaw sensitive it becomes. However, because some load bearing capacity is required for toughness, high toughness can be achieved by a high trade off of certain factors.

Crystallinity increases both stiffness and yield strength, resulting usually in decreased toughness. This is true below T_g in most amorphous plastics, and below or above the T_g in a substantially crystalline plastic. However, above the T_g in a plastic having only moderate crystallinity increased crystallinity improves its toughness. Furthermore, an increase in molecular weight from low values increases toughness, but with continued increases, the toughness begins to drop.

Cross-linking produces some dimensional stability and improves toughness in a non-crystalline type of plastic above the T_g, but

high levels of cross-linking lead to embrittlement and loss of toughness. This is one of the problems with TSs for which an increase in T_g is desired. Increased cross-linking or stiffening of the chain segments increases the T_g, but it also decreases toughness. A popular way to increase toughness is to blend, compound, or copolymerize a brittle plastic with a tough one. Although some loss in stiffness is usually encountered, the result is a satisfactory combination of properties.

Thermal Property

Figure 5-6 and Tables 5-3 to 5-5 provide an introductory guide to the different thermal properties of plastics. Heat resistance properties of plastics retaining 50% of properties obtainable at room temperature with plastic exposure and testing at elevated temperatures are shown in Fig. 5-6 for the general family or group type.

Zone 1: acrylic, cellulose esters, crystallizable block copolymers, LDPE, PS, vinyl polymers, SAN, SBR, and urea-formaldehyde.

Zone 2: acetal, ABS, chlorinated polyether, ethyl cellulose, ethylene-vinyl acetate copolymer, furan, ionomer, phenoxy, polyamides, PC, RDPE, PET, PP, PVC, and urethane.

Zone 3: polychlorotrifluoroethylene, and vinylidene fluoride.

Zone 4: alkyd, fluorinated ethylene-propylene, melamine-formaldehyde, phenol-furfural, and polysulfone.

Zone 5: acrylic, diallyl phthalate, epoxy, phenol-formaldehyde, TP polyester, and polytetrafluoroethylene.

Zone 6: parylene, polybenzimidazole, polyphenylene, and silicone.

Zone 7: polyamide-imide, and polyimide;

Zone 8: plastics now being developed using rigid linear macromolecules rather than crystallization and cross-linking, etc.

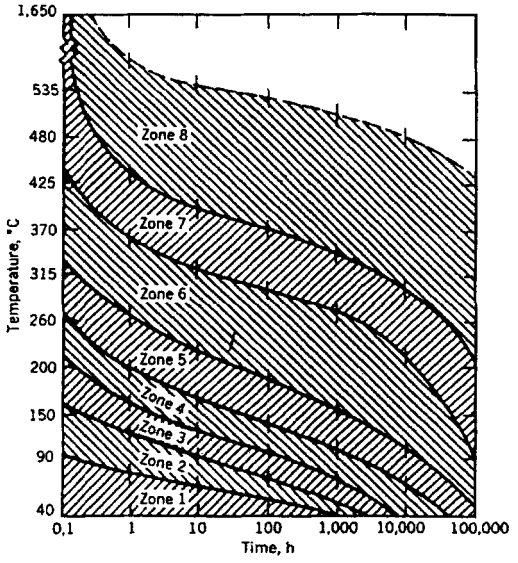

Fig. 5-6 Guide to heat resistance with 50% retention of properties.

Specific family or group of plastics (polyethylene, polyvinyl chlorides, etc.) are compounded or alloyed to provide different properties and/or processing behaviors. Thus a plastic listed in Fig. 5-6 could have different heat resistance properties.

Deflection Temperature Under Load

The DTUL, also called the heat distortion temperature (HDT) of a plastic is a method to guide or assess its load-bearing capacity at an elevated temperature. Details on the method of testing are given in ASTM D648. Basically a 1.27 cm (½ in.) deep plastic test bar is mounted on supports 10.16 cm (4 in.) apart and loaded as a beam. A bending stress of either 66 psi or 264 psi (455 gPa or 1,820 gPa) is applied at the center of the span.

The test is conducted in a bath of oil, with the temperature increased at a constant rate of 2°C per minute. The DTUL is the temperature at which the sample attains a deflection of 0.0254 cm (0.010 in.). This test is only a guide. It represents a method that could be correlated to product designs, but as with most other tests conducted on test specimens and not on a finished product, it is just a guide (Fig. 5-7).

In this test, if the specimen contains internal stresses the value will be lower than a specimen with no stresses. In fact, the test can

Table 5-3 Examples of plastics in elevated temperature applications

Polymer	Comments
Polyphenyls	Decompose at 530°C (986°F); infusible, insoluble polymers.
Polyphenylene oxide	Decomposes close to 500°C (932°F); heat cures above 150°C (302°F) to elastomer; usable heat range −135–185°C (−211–365°F).
Polyphenylene sulfide	Melts at 270–315°C (578–599°F); crosslinked polymer stable to 450°C (842°F) in air: adhesive and laminating applications.
Polybenzyls; polyphenethyls	Fusible, soluble, and stable at 400°C (752°F); low molecular weight.
Parylenes (poly-*p*-xylylene)	Melt above 520°C (968°F); insoluble; capable of forming films; poor thermal stability in air; stable to 400–525°C (752–977°F) in inert atmosphere.
Polyterephthalamides	Melting points up to 455°C (851°F); fibers have good tenacity, elongation, modulus.
Polysulfanyldibenzamides	Melting points up to 330°C (626°F); soluble; good fiber properties.
Polyhydrazides	Dehydrate at 200°C (392°F) to over 400°C (752°F) to form polyoxadiazoles; good fiber properties.
Polyoxamides	Some melting points above 400°C (752°F); give clear, flexible films.
Phenolphthalein polymers	Melting points of 300°C (572°F) to over 400°C (752°F); formable into fiber and film.
Hydroquinone polyesters	Soluble polymers with melting points of 335°C (635°F) to over 400°C (752°F).
Polyhydroxybenzoic acids	Films melt at 380–450°C (716–842°F); stable to oxidation but not to hydrolysis; tough, flexible films; good thermal stability.
Polyimides	Commercial film, coating, and resin stable up to 600°C (1112°F); continuous use up to 300°C (572°F).
Polyarylsiloxanes	Good thermal stability 400–500°C (752–932°F); coatings, adhesives.
Carboranes	Stable in air and nitrogen at 400–450°C (752–842°F); elastomeric properties for silane derivatives up to 538°C (1000°F); adhesives.
Polybenzimidazoles	Developmental laminating resin, fiber, film; stable 24 hours at 300°C (572°F) in air.
Polybenzothiazoles	Stable in air at 600°C (1112°F); cured polymer soluble in concentrated sulfuric acid.
Polyquinoxalines	Stable in air at 500°C (932°F); tough, somewhat flexible resins; make film, adhesive.
Polyphenylenetriazoles	Thermally stable to 400–500°C (752–932°F); make film, fiber, coatings.
Polydithiazoles	Decompose at 525°C (977°F); soluble in concentrated sulfuric acid.
Polyoxadiazoles	Decompose at 450–500°C (842–932°F); can be made into fiber or film.
Polyamidines	Stable to oxidation up to 500°C (932°F); can make flexible elastomer.
Pyrolyzed polyacrylonitrile	Stable above 900°C (1625°F); fiber resists abrasion with low tenacity.
Polyvinyl isocyanate ladder polymer	Soluble polymer that decomposes at 385°C (725°F); prepolymer melts above 405°C (761°F).
Polyamide-imide	Service temperatures up to 288°C (550°F); amenable to fabrication.
Polysulfone	Thermoplastic; use temperature −102°C (−152°F) to greater than 150°C (302°F); acid and base resistant.
Polybenzaylene benzimidazoles (pyrrones)	Thermally stable to 600°C (1112°F); insoluble in common solvents; good mechanical properties.
Polybenzoxazoles	Stable in air to 500°C (932°F); insoluble in common solvents except sulfuric acid; nonflammable; chemical resistant; film.
Ionomer	High melt and tensile strength; tough; resilient; oil and solvent resistant; adhesives, coatings.

(*Continues*)

Table 5-3 (*Continued*)

Polymer	Comments
Diazadiphosphetidine	Thermoplastic up to 350°C (662°F); thermosetting at 357°C (707°F); cured material has good thermal stability to 500°C (932°F); amenable to fabrication.
Phosphorous amide epoxy	Soluble B-staged material; amenable to fabrication; good thermal stability.
Phosphonitrilic	Retention of properties in air up to 399°C (750°F).
Metal polyphosphinates	Polymers stable to better than 400°C (752°F).
Phenylsilesesquioxanes (phenyl-T ladder polymers)	Soluble; high molecular weight; infusible; improved tensile strength; high thermal stability to 525°C (977°F) in air; film forming.

be used to determine the degree of internal stress. Since a stress and the deflection for a certain depth of test bar are specified, this test may be thought of as establishing the temperature at which the flexural modulus decreases to particular values: 35,000 psi (240 MPa) at 66 psi load stress, and 140,800 psi (971 MPa) at 264 psi.

Coefficient of Linear Thermal Expansion

The specimen can be square or round to fit a dilatometer test tube in a free sliding manner. The length is governed by the sensitivity of dial gauge, the expected expansion, and the accuracy desired. The specimen is mounted in the dilatometer and placed in a bath of either −22°F (−30°C) or 87°F (+30°C) until the temperature of the bath is reached. When this takes place, the indicator dial is read showing the expansion or contraction of the specimen. These readings are compared with measurement of specimen length prior to placing it in the dilatometer.

With the application of plastics in combination with other materials, the coefficient of expansion plays an important role in making design allowances for expansions (also contractions) of various materials at different temperatures so that satisfactory functions of products are ensured.

Table 5-4 Examples of ignition and flash temperatures

	Self Ignition		Flash Ignition	
	°F	°C	°F	°C
Polyethylene	662	350	644	340
Polypropylene	1022	550	968	520
Polytetrafluoroethylene	1076	580	1040	560
Polyvinyl chloride	842	450	734	390
Polyvinyl fluoride	896	480	788	420
Polystyrene	914	490	662	350
SBR (Styrene Butadiene Rubber)	842	450	680	360
ABS (Acrylonitrile Butadiene Styrene	896	480	734	390
Polymethyl methacrylate	806	430	572	300
PAN (Polyacrylonitrile)	1040	560	896	480
Cellulose (paper)	446	230	410	210
Cellulose acetate	878	470	644	340
66 Nylon cast	842	450	788	420
66 Nylon spun and drawn	986	530	914	490
Polyester	896	480	824	440

Table 5-5 Effects of elevated temperature and chemical agents on stability of plastics

Plastic Material	Acetal Copolymer	Acetal Homopolymer	Nylon 6/6[1]	Thermoplastic Polyester (PBT)	Thermoplastic Polyester (PET)	Polyester Elastomer	Liquid Crystal Polymer*	Polyphenylene Sulfide*	Polyarylate	Polycarbonate	Polysulfone*	Modified Polyphenylene Oxide	Polypropylene	ABS	316 Stainless Steel	Carbon Steel	Aluminum
	Environment																
	Temperature (°F)																
	77 (25°C)	200 (93.3°C)	77	200	77	200	77	200	77	200	77	200	77	200	77	200	% Change by Weight
Acetals	1–4	2–4	1	2	1–2	4	1–3	2–5	1–5	2–5	5	5	5	5	1	2–3	0.22–0.25
Acrylics	5	5	2	3	5	5	1	3	2	5	4	4–5	5	5	5	5	0.2–0.4
Acrylonitrile-Butadiene-Styrenes (ABS)	4	5	2	3–5	3–5	5	1	2–4	1	2–4	1–4	5	1–5	5	3–5	5	0.1–0.4
Aramids (aromatic polyamide)	1	1	1	1	1	1	2	3	4	5	3	4	2	5	1	2	0.6
Cellulose acetates (CA)	2	3	2	3	3	4	2	3	3	5	3	5	3	5	5	5	2–7
Cellulose acetate butyrates (CAB)	4	5	1	3	3	4	2	4	3	5	3	5	3	5	5	5	0.9–2.0
Cellulose acetate propionates (CAP)	4	5	1	3	3	4	1	2	3	5	3	5	3	5	5	5	1.3–2.8
Diallyl phthalates (DAP, filled)	1–2	2–4	2	3	2	4	2	3	2	4	1–2	2–3	2	4	3–4	4–5	0.2–0.7
Epoxies	1	2	1	2	1–2	3–4	1	1–2	1	2	2–3	3–4	4	4–5	2	3–4	0.01–0.10
Ethylene copolymers (EVA) (ethylene-vinyl acetates)	5	5	5	5	5	5	1	2	1	5	1	5	1	5	2	5	0.05–0.13
Fluorocarbons: Ethylene/tetrafluoro-ethylent copolymers (ETFE)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	<0.03
Fluorocarbons: Fluorinated ethylene propylenes (FEP)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	<0.01
Fluorocarbons: Perfluoroalkoxies (PFA)	1.	·1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	<0.03
Fluorocarbons: Polychlorotrifluoro-ethylenes (CTFE)	1	1	1	1	3	4	1	1	1	1	1	1	1	1	1	1	0.01–0.10
Fluorocarbons: Polytetrafluoro-ethylenes ®(TFE)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Furans	1	1	1	1	1	1	2	2	2	2	1	1	5	5	1	1	0.01–0.20
Ionomers	2	4	1	4	4	4	1	4	1	4	2	4	1	5	1	4	0.01–1.4
Melamines (filled)	1	1	1	1	1	1	2	3	2	3	2	3	2	3	1	2	0.01–1.30
Nitriles (high barrier alloys of ABS or SAN)	1	4	1	2–4	1–4	2–5	1	2–4	1	2–4	2–5	5	3–5	5	1–5	5	0.2–0.5
Nylons	1	1	1	1	1	2	1	2	2	3	5	5	5	5	1	1	0.2–1.9
Phenolics (filled)	1	1	1	1	1	1	2	3	3	5	1	1	4	5	2	2	0.1–2.0
Polyallomers	2	4	2	4	4	5	1	1	1	1	1	3	1	4	1	3	<0.01

[1] A rating of 1 indicates greatest stability.

The difference in thermal expansion between the usual commodity plastics and steel is very large. It is to be noted that some plastic material changes in length rather abruptly at some temperatures, beyond the limits of the test condition. In such cases, a special investigation should be instigated, and the coefficient of expansion established under temperatures of usage. However there are plastics that can be compounded to match or even have less thermal expansion than steel, etc.

This test shows the reversible linear thermal expansion. The accuracy of these results may be affected by factors in certain plastics such as loss of plasticizer, solvent, relieving of stresses, etc. When a product demands most precise data, the factors mentioned should be considered for their possible influence on the information.

Brittleness Temperature

The conditioned specimens are cantilevered from the sample holder in the test apparatus, which has been brought to a low temperature (that at which the specimens would be expected to fail). When the

Table 5-5 (*Continued*)

Plastic Material	Environment															
	Aromatic Solvents		Aliphatic Solvents		Chlorinated Solvents		Weak Bases and Salts		Strong Bases		Strong Acids		Strong Oxidants		Esters and Ketones	24-H Water Absorption
	Temperature (°F)															
	77 (25°C)	200 (93.3°C)	77	200	77	200	77	200	77	200	77	200	77	200	77	200	% Change by Weight
Polyamide-imides	1	1	1	1	2	3	1	1	3	4	2	3	2	3	1	1	0.22–0.28
Polyarylsulfones (PAS)	4	5	2	3	4	5	1	2	2	2	1	1	2	4	3	4	1.2–1.8
Polybutylenes (PB)	3	5	1	5	4	5	1	2	1	3	1	3	1	4	1	3	<0.01–0.3
Polycarbonates (PC)	5	5	1	1	5	5	1	5	5	5	1	1	1	1	5	5	0.15–0.35
Polyesters (thermoplastic)	2	5	1	3–5	3	5	1	3–4	2	5	3	4–5	2	3–5	2	3–4	0.06–0.09
Polyesters (thermoset-glass fiber filled)	1–3	3–5	2	3	2	4	2	3	3	5	2	3	2	4	3–4	4–5	0.01–2.50
Polyethylenes (LDPE-HDPE—low density to high density)	4	5	4	5	4	5	1	1	1	1	1–2	1–2	1–3	3–5	2	3	0.00–0.01
Polyethylenes (UHMWPE—ultrahigh molecular weight)	3	4	3	4	3	4	1	1	1	1	1	1	1	1	3	4	<0.01
Polyimides	1	1	1	1	1	1	2	3	4	5	3	4	2	5	1	1	0.3–0.4
Polyphenylene oxides (PPO) (modified)	4	5	2	3	4	5	1	1	1	1	1	2	1	2	2	3	0.06–0.07
Polyphenylene sulfides (PPS)	1	2	1	1	1	2	1	1	1	1	1	1	1	2	1	1	<0.05
Polyphenylsulfones	4	4	1	1	5	5	1	1	1	1	1	1	1	1	3	4	0.5
Polypropylenes (PP)	2	4	2	4	2–3	4–5	1	1	1	1	1	2–3	2–3	4–5	2	4	0.01–0.03
Polystyrenes (PS)	4	5	4	5	5	5	1	5	1	5	4	5	4	5	4	5	0.03–0.60
Polysulfones	4	4	1	1	5	5	1	1	1	1	1	1	1	1	3	4	0.2–0.3
Polyurethanes (PUR)	3	4	2	3	4	5	2–3	3–4	2–3	3–4	2–3	3–4	4	4	4	5	0.02–1.50
Polyvinyl chlorides (PVC)	4	5	1	5	5	5	1	5	1	5	1	5	2	5	4	5	0.04–1.00
Polyvinyl chlorides—chlorinated (CPVC)	4	4	1	2	5	5	1	2	1	2	1	2	2	3	4	5	0.04–0.45
Polyvinylidene fluorides (PVDF)	1	1	1	1	1	1	1	1	1	2	1	2	1	2	3	5	0.04
Silicones	4	4	2	3	4	5	1	2	4	5	3	4	4	5	2	4	0.1–0.2
Styrene acrylonitriles (SAN)	4	5	3	4	3	5	1	3	1	3	1	3	3	4	4	5	0.20–0.35
Ureas (filled)	1	3	1	3	1	3	2	3	2	3	4	5	2	3	1	2	0.4–0.8
Vinyl esters (glass-fiber filled)	1	3	1–2	2–4	1–2	4	1	3	1	3	1	2	2	3	3–4	4–5	0.01–2.50

A rating of 1 indicates greatest stability.

specimens have been in the test medium for 3 minutes, a single impact is administered, and the samples are examined for failure. Failures are total breaks, partial breaks, or any visible cracks. The test is conducted at a range of temperatures producing varying percentages of breaks. From these data, the temperature at which 50% failure would occur is calculated or plotted and reported as the brittleness temperature of the material according to this test.

This test is of some use in judging the relative merits of various materials for low-temperature flexing or impact. However, it is specifically relevant only for materials and conditions specified in the test, and the values cannot be directly applied to other shapes and conditions.

The brittleness temperature does not put any lower limit on service temperature for end use products. The brittleness temperature is sometimes used in specifications.

Thermal Aging

Section UL 746B provides a basis for selecting high-temperature plastics and provides a long-term thermal-aging index, the RTI or relative thermal index. The testing procedure calls for test specimens in selected thicknesses to be oven aged at certain elevated temperatures (usually higher than the expected operating temperature, to accelerate the test), then be removed at various intervals and tested at room temperature.

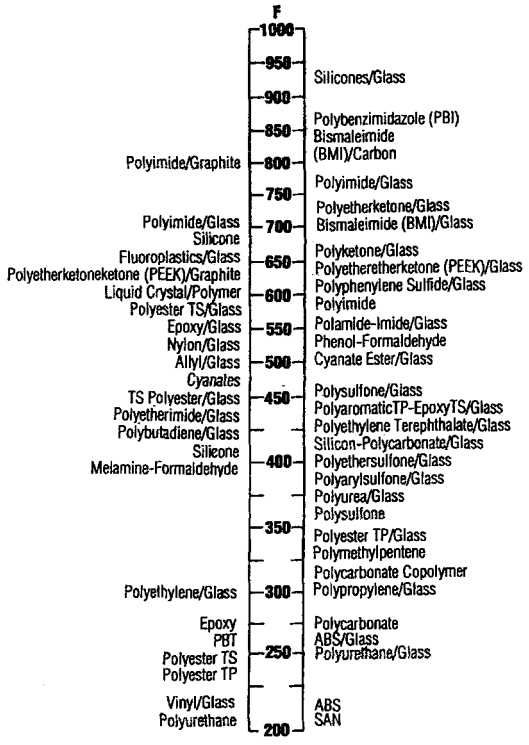

Fig. 5-7 Guide to heat resistance based on the heat-distortion temperature per ASTM D 648 at 264 psi.

Another reason for using higher temperatures is that for an application requiring long-term exposure a candidate plastic is often required to have an RTI value higher than the maximum application temperature. The properties tested can include mechanical strength, impact resistance, and electrical characteristics. A plastic's position in a test's RTI is based on the temperature at which it still retains 50% of its original properties.

The time required to produce a 50% reduction in properties is selected as an arbitrary failure point. These times can be gathered and used to make a linear Arrhenius plot of log time versus the reciprocal of the absolute exposure temperature. An Arrhenius relationship is a rate equation followed by many chemical reactions. A linear Arrhenius plot is extrapolated from this equation to predict the temperature at which failure is to be expected at an arbitrary time that depends on the plastic's heat-aging behavior, which are usually 11,000 hours, with a minimum of 5,000 hours. This value is the RTI.

As practiced by the UL, the procedure for selecting an RTI from Arrhenius plots usually involves making comparisons to a control standard material and other such steps to correct for random variations, oven temperature variations, condition of the specimens, and others. The stress-strain and impact and electrical properties frequently do not degrade at the same rate, each having their own separate RTIs. Also, since thicker specimens usually take longer to fail, each thickness will require a separate RTI.

The UL uses RTIs as a guideline to qualify materials for many of the standard appliances and other electrical products it regulates. This testing is done in a conservative manner qualified by judgments based on long experience with such devices; UL does not apply indexes automatically. In general, these RTIs are very conservative and can be used as safe continuous-use temperatures for low-load mechanical products.

Other Heat Test

There are different heat tests, some being specific to a product environment. There are those for temperature and also humidity. With certain materials, humidity combined with elevated temperatures has a significant effect on the material's behavior. This effect would not be evident in the conventional heat distortion test (HDT).

Test specimens can also be used to simulate some degree of warpage. Figure 5-8 compares unreinforced and reinforced glass fiber-TS polyester flexural-type specimens at different temperatures in a droop test (with a center support), sag test (end supports), and an expansion test (bolted at three points). The study for this particular test is conducted at various temperatures.

Thus by analyzing the thermal limits of the various materials available, starting with the maximum and minimum environmental temperatures under which a product must operate and adding any thermal increase

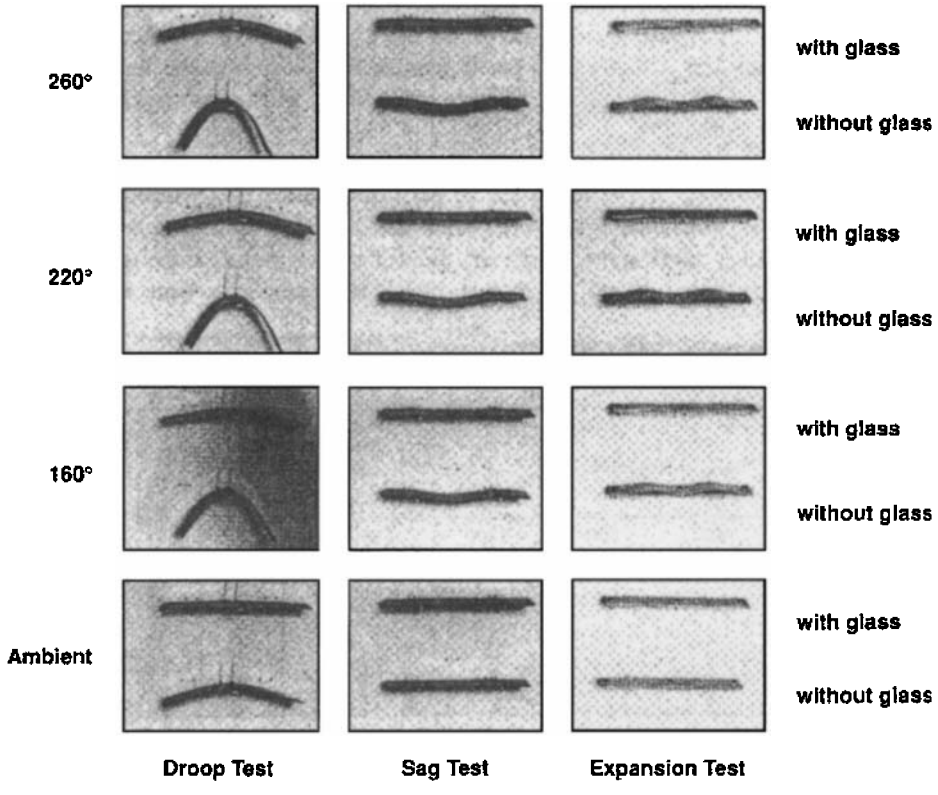

Fig. 5-8 Example of droop, sag, and expansion tests using RP samples.

from hysteresis heat that develops from flex or vibration and so on will at least tell the designer which materials cannot be used.

The ratings given the designer will also provide some idea of the short-term stiffness to be expected of various materials at elevated temperatures, as well as their thermal aging resistance with regard to certain properties. Establishing two parameters, ASTM D 648 and UL 746B, for a variety of materials provides the designer with a reasonable starting point for initially assessing materials for high-temperature applications. Most high-performance plastics are filled compounds, since fillers and reinforcements (Fig. 5-9) generally enhance high temperature strength and stiffness.

A general definition for a high-temperature plastic is one having a thermal value in terms of ASTM D 648 and UL 746B higher than 149°C (300°F). There are numerous plastics that are both processable and have useful mechanical properties in the 149 to 260°C (300 to 500°F) range (Fig. 5-10). Their costs are usually high, but so is their performance.

High-temperature plastics fall into the usual categories of TSs and TPs. The TSs are used principally by the aircraft and aerospace markets but also for automotive, industrial, medical, and electronic products. Epoxies are principally used, with other plastics being TS polyesters, phenolics, and urethanes. These plastics are usually reinforced with the high strength fibers seen in Fig. 5-9, individually or in combination with S-glass, graphite, aramid, and others. About 85wt% of all RPs used in conventional-temperature environments only require E-glass (14).

High-temperature TPs are available to compete with TSs, metals, ceramics, and other nonplastic materials. The heat-resistant TPs include polyetheretherketone (PEEK) and polyethersulfone (PES), polyamideimide, liquid crystal polymer (LCP) and others.

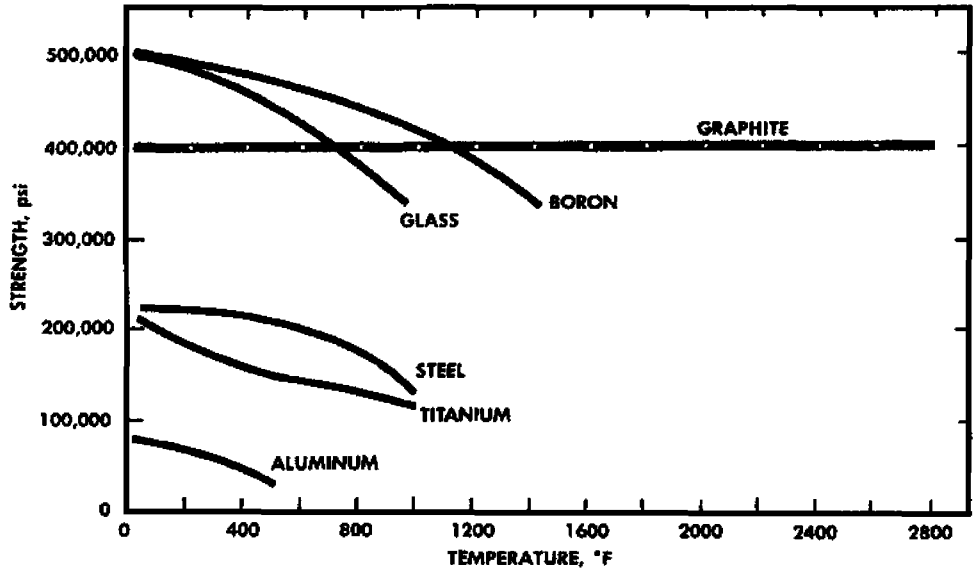

Fig. 5-9 Examples of tensile strengths vs. temperature in high performance materials.

These TPs have high inherent heat resistance and offer such other advantages over TSs as higher toughness and ease of processing. Some of these plastics are amorphous with a high T_g such as PES, and some like PEEK and the liquid crystal polymer (LCP) are highly crystalline. Some high-temperature plastics are commercially available in neat form, with most being available only in the filled or reinforced form for such high-performance products. Many of these plastics can be processed on standard or modified TP processing equipment, which requires melting at higher temperatures than commodity or engineering plastics, but others, like the polyimides, may require machining into shape.

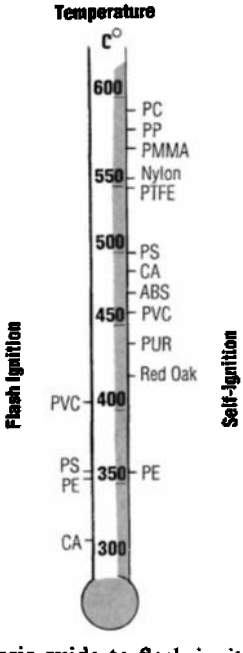

Fig. 5-10 Basic guide to flash ignition and self-ignition temperatures (per ASTM D 1929) for plastics and red wood.

The direction of high-temperature TSs appears to be toward more toughness using new processing techniques for the aviation and aerospace markets. The high-temperature TPs have been receiving considerable attention as possible replacements for TSs in advanced RPs because of their higher toughness, faster processing, and ease of repair. The TPs are being promoted in both unreinforced and reinforced forms as molding and extrusion materials. Their high continuous use temperatures, combined with their good chemical, water, and flame resistance and low smoke generation, are finding new applications, particularly as their price is reduced through higher volume usage. The growth of TP-TS hybrids, offering TPs' ready processing combined with TSs' long-term dimensional stability, are also positive.

Electrical Property

The resistance of most plastics to the flow of direct current is very high. Both surface and volume electrical resistivities are important properties for applications of plastics insulating materials. The volume resistivity is the electrical resistance of the material measured in ohms as though the material was a conductor. Insulators will not sustain an indefinitely high voltage; as the applied voltage is increased, a point is reached where a drastic decrease in resistance takes place accompanied by a physical breakdown of the insulator. This is known as the dielectric strength, which is the electric potential in volts, which would be necessary to cause the failure of a 1/8-in. thick insulator (Chapter 4, **ELECTRICAL/ELECTRONICS PRODUCT**).

Electrical Resistance

Specimens for these tests may be any practical form, such as flat plates, sheets, or tubes. These tests describe methods for determining the several properties defined below. Two electrodes are placed on or embedded in the surface of a test specimen. Different properties are obtained.

Insulation resistance is the ratio of direct voltage applied to the electrodes to the total current between them; dependent upon both volume and surface resistance of the specimen. In materials used to insulate and support components of an electrical network, it is generally desirable to have insulation resistance as high as possible.

Volume resistivity is the ratio of the potential gradient parallel to the current density.

Surface resistivity is the ratio of the potential gradient parallel to the current along its surface to the current per unit width of the surface. Knowing the volume and surface resistivity of an insulating material makes it possible to design an insulator for a specific application.

Volume resistance is the ratio of direct voltage applied to the electrodes to that portion of current between them that is distributed through the volume of the specimen.

Surface resistance is the ratio of the direct voltage applied to the electrodes to that portion of the current between them that is in a thin layer of moisture or other semiconducting material which may be deposited on the surface. High volume and surface resistance are desirable in order to limit the current leakage of the conductor that is being insulated.

Arc Resistance

This test shows the ability of a material to resist the action of an arc of high voltage and low current close to the surface of the insulation in tending to form a conducting path therein. The arc resistance data are of relative value only for distinguishing materials of nearly identical composition, such as for quality control, development, or identification.

Dielectric Strength

Specimens are thin sheets or plates having parallel plane surfaces and are of a size sufficient to prevent flashing over. Dielectric strength varies with thickness and, therefore, specimen thickness must be reported. The dielectric strength varies inversely with the thickness of the specimen. The dielectric strength of plastics will drop sharply if holes, bubbles, or contaminants are present in the specimen being tested.

Since temperature and humidity affect results, it is necessary to condition each type of material as directed in the specification for that material. The test for dielectric strength must be run in the conditioning chamber or immediately after removing the specimen from the chamber.

The specimen is placed between heavy cylindrical brass electrodes, which carry electrical current during the test. There are two ways of running this test for dielectric strength. In the short-time test the voltage is increased from zero to breakdown at a uniform rate. The precise rate of voltage rise is specified in the governing material specifications. In the step-by-step test the initial

voltage applied is 50% of breakdown voltage shown by the short-time test. It is increased at rates specified for each type of material, and the breakdown level is noted. Breakdown by these tests means passage of sudden excessive current through the specimen and can be verified by instruments and by visible damage to the specimen.

This test is an indication of the electrical strength of a material as an insulator. The dielectric strength of an insulating material is the voltage gradient at which electric failure or breakdown occurs as a continuous arc (the electrical property analogous to tensile strength in mechanical properties). The dielectric strength of materials varies greatly with several conditions such as humidity and geometry, and it is not possible to directly apply the standard test values to field use unless all conditions, including specimen dimensions, are the same. Because of this, the dielectric strength test results are of relative rather than absolute value as a specification guide.

Dielectric Constant and Dissipation Factor

The specimen may be a sheet of any size convenient to test, but should have uniform thickness. The test may be run at standard room temperature and humidity, or in special sets of conditions as desired. In any case, the specimens should be preconditioned to the set of conditions used. Electrodes are applied to opposite faces of the test specimen. The capacitance and dielectric loss are then measured by comparison or substitution methods in an electric bridge circuit. From these measurements and the dimensions of the specimen, dielectric constant and loss factor are computed.

The dissipation factor is a ratio of the real power (in-phase power) to the reactive power (power 90° out of phase). It is also defined as: (1) IT is the ratio of conductance of a capacitor in which the material is the dielectric to its susceptance, (2) IT is the ratio of its parallel reactance to its parallel resistance; it is the tangent of the loss angle and the cotangent of the phase angle, and (3) IT is a measure of the conversion of the reactive power to real power, showing as heat.

The dielectric constant is the ratio of the capacity of a condenser made with a particular dielectric to the capacity of the same condenser with air as the dielectric. For a material used to support and insulate components of an electrical network from each other and ground, it is generally desirable to have a low level of dielectric constant. For a material to function as the dielectric of a capacitor, on the other hand, it is desirable to have a high value of dielectric constant, so that the capacitor may be physically as small as possible.

The loss factor is the product of the dielectric constant and the power factor, and is a measure of total losses in the dielectric material.

Optical Property

Examples of plastics' transparent properties are shown in Table 5-6. A basic behavior of the appearance of a transparent material, that is one that transmits light, is its transmittance: the ratios of the intensities of light passing through and the light incident on the specimen. Similarly, the appearance of an opaque material (one which may reflect light but does not transmit it) is characterized by its reflectance, the ratio of the intensities of the reflected and incident light. A translucent substance is one that transmits part and reflects part of the light incident on it. Gloss is the geometrically selective reflection of a surface responsible for its shiny or lustrous appearance. This property may be measured by the use of various photoelectric instruments or simply by observation.

Haze and Huminous Transmittance

In this test, haze of a specimen is defined as the percentage of transmitted light that, in passing through the specimen, deviates more than 2.5° from the incident beam by forward scattering. Basically it is defined as the ratio of transmitted to incident light.

Table 5-6 Examples of plastics' transparent properties

Properties	ASTM Method	Units	Methyl Methacrylate (Acrylic)	Polystyrene (Styrene)	Polycarbonate	Methyl Methacrylate Styrene Copolymer
Refractive index (n_D)	D 542		1.491	1.590	1.586	1.562
Abbe. value (ν)	D 542		57.2	30.9	34.7	35
$dn/dt \times 10^{-5}$/°C			8.5	12.0	14.3	14.0
Haze (%)	D 1003	%	<2	<3	<3	<3
Luminous transmittance (0.125-in. thickness)	D 1003	%	92	88	89	90
Critical angle (i_c)		degree	42.2	39.0	39.1	39.6
Deflection temperature	D 648–56	°F				
3.6 F/min., 264 psi			198	180	280	
3.6 F/min., 66 psi			214	230	270	212
Coefficient of linear thermal expansion	D 696–44	in./in./°F $\times 10^{-6}$	3.6	3.5	3.8	3.6
Recommended max. cont. service temp.		°F	198	180	255	200
Water absorption (immersed 24 hrs. at 73°F)	D 570–63	%	0.3	0.2	0.15	0.15
Specific gravity (density)	D 792		1.19	1.06	1.20	1.09
Hardness (0.25-in. sample)	D 785–62		M 97	M 90	M 70	M 75
Impact strength (Izod Notch)	D 256	ft.-lb./in.	0.3–0.5	0.35	12–17	
Dielectric strength	D 149–64	V/mil	500	500	400	450
Dielectric constant						
60 HZ	D 150		3.7	2.6	2.90	3.40
10^6 Hz			22.2	2.45	2.88	2.90
Power factor						
60 Hz	D 150		0.05	0.0002	0.0007	0.006
10^6 Hz			0.03	0.0002–0.0004	0.0075	0.013
Volume resistivity	D 257	ohm-cm	10^{18}	$>10^{16}$	8×10^{16}	10^{15}

These qualities are considered in most applications for transparent plastics, forming a basis for directly comparing the transparency of various grades and types of plastic. The data are of value when a material is considered for optical purposes. Many transparent plastics do not have water clarity, and, for this reason, the data should indicate whether the material was natural or tinted when tested.

Luminous Reflectance

Opaque specimens should have at least one plane surface. Translucent and transparent

specimens must have two surfaces that are plane and parallel. This test is the primary method for obtaining colormetric data. The property determined that is of design interest is luminous transmittance.

Opacity and Transparency

Opacity or transparency is important when the amount of light to be transmitted is a consideration. These properties are usually measured as haze and luminous transmittance. As reviewed haze is defined as the percentage of transmitted light through a test specimen that is scattered more than 2.5° from the incident beam. Luminous transmittance is the ratio of transmitted light to incident light. Table 5-7 provides the optical and various other properties of different transparent plastics.

Some definitions of key terms used in identifying optical conditions are reviewed in Chapter 4, **TRANSPARENT AND OPTICAL PRODUCTS, Properties, Performances, and Products.**

Abrasion and Mar Resistance

In this test for transparent plastics, the loss of optical effects is measured when a specimen is exposed to the action of a special abrading wheel. In one type of test the amount of material lost by a specimen is determined when the specimen is exposed to falling abrasive particles or to the action of an abrasive belt. In another test, the loss of gloss due to the dropping of loose abrasive on the specimen is measured. The results produced by the different tests may be of value for research and development work when it is desired to improve a material with respect to one of the test methods. The variables that enter into tests of this type are

Table 5-7 Notable behaviors of some transparent plastics

Generic Family	Notable Characteristics
Transparent ABS	Good impact properties, good processibility
Acrylic (PMMA)	Excellent resistance to outdoor exposure, crystal clarity
Allyl diglycol carbonate	Good abrasion/chemical resistance, thermoset
Cellulosics	Heat sensitive, limited chemical resistance, good toughness
Nylon, amorphous	Excellent abrasion resistance, moisture sensitive
PET, PETG	Good barrier properties, not weatherable, clarity dependent on processing, orientation greatly increases physical properties
Polyarylate	Excellent UV resistance, high heat distortion
Polycarbonate	Excellent toughness, good thermal/flammability characteristics
Polyetherimide	Good chemical/solvent resistance, good thermal/flammability properties, inherent high color
Polyphthalate carbonate	Good thermal properties, autoclavable
Polyethersulfone	Excellent thermal stability, resists creep
Poly-4–methylpentene–1	UV/moisture sensitive, high crystalline melting point, lowest density of all thermoplastics
Polyphenylsulfone	Excellent thermal stability, resists creep, inherent high color
Polystyrene	Excellent processibility, poor UV resistance, brittle
Polysulfone	Excellent thermal/hydrolytic stability, poor weatherability/ impact strength
PVC, rigid	Excellent chemical resistance/electrical properties, weatherable, decomposition evolves HCl gas
Styrene acrylonitrile	Good stress-crack and craze resistance, brittle
Styrene butadiene	Good processibility, no stress whitening
Styrene maleic anhydride	Higher-heat styrenic, brittle
Styrene methyl methacrylate	Good processibility, slightly improved weatherability
Thermoplastic urethane, rigid	Excellent chemical/solvent resistance, good toughness

so numerous that it is questionable how the information from such tests could be used. Some of the factors are type of abrasive, shape of abrading particle, nature of plastic material, speed of action on the plastic, shape of the part and its temperature, the manner in which the abrasive is attached to the backing, and the bonding agent.

Currently, these tests are of no practical value to the designer and the only approach to the problem of scratch, mar, and abrasion resistance is to simulate actual performance needs. For optical purposes, a cast sheet in the allyl family of plastics known as CR39 has been used as a standard of comparison in evaluating scratch and mar resistance of a material. The CR39 is used for eye lenses and other optical products where the advantages of plastics are a consideration. Coatings have been developed for polycarbonate, acrylics, and other plastics that dramatically improve the scratch and mar resistance of these materials.

Weathering

Outdoor Weathering

The specimen has no specified size. Specimens for this test may consist of any standard fabricated test specimen or cut/punch pieces of sheet or machined sample. Specimens are mounted outdoors on racks slanted at 45° and facing south. It is recommended that concurrent exposure be carried out in many varied climates to obtain the broadest, most representative total body of data. Sample specimens are kept indoors as controls and for comparison. Reports of weathering describe all changes noted, areas of exposure, and period of time.

Outdoor testing is the most accurate method of obtaining a true picture of other resistance. The only drawback of this test is the time required for several years' exposure that are usually located in different climatic zones around the world. A large number of specimens are usually required to allow periodic removal and to run representative laboratory tests after exposure.

Accelerated Weathering

The specimen may be any shape. Artificial weathering has been defined by ASTM as "The exposure of plastics to cyclic laboratory conditions involving changes in temperature, relative humidity, and ultraviolet (UV) radiant energy, with or without direct water spray, in an attempt to produce changes in the material similar to those observed after long-term continuous outdoor exposure."

Three types of light sources for artificial weathering are in common use: (1) enclosed UV carbon arc [7.5 UV energy output, approx. (x sunlight)], (2) open-flame sunshine carbon, and (3) water-cooled xenon arc. Selection of the light source involves many conditions and circumstances, such as the type of material being tested, product service conditions, previous testing experience, or the type of information desired.

Since weather varies from day to day, year to year, and place to place, no precise correlation exists between artificial laboratory weathering and natural outdoor weathering. However, standard laboratory test conditions produce results with acceptable reproducibility and in general agreement with data obtained from long-time outdoor exposures.

Fairly rapid indications of weatherability are therefore obtainable on samples of known materials that through testing experience over a period of time have general correlations established. There is no artificial substitute for precisely predicting outdoor weatherability on materials with no previous weathering history. Weatherometers produce conditions to accelerate effects that would be observed in specimens exposed outdoors.

Accelerated Exposure to Sunlight

The Atlas Type FDA-IR Fadeometer is used primarily to check and compare color stability. Besides determining the stability of various pigments needed to provide both standard and custom colors, the Fadeometer is helpful in preliminary studies of various stabilizers, dyes, and pigments compounded in plastics to prolong their useful life.

It is primarily for testing materials to be used in products subject to indoor exposure and to sunlight. Exposure in the Fadeometer cannot be related directly to exposure in direct sunlight, partially because other weather factors are always present outdoors.

Conditioning Procedure

As reviewed it is important that test specimens or products be properly prepared based on available specifications and/or standards that provide controlled conditioning procedures when conducting weathering as well as all other tests. The following is one example. There are other conditions set forth to provide for testing at higher or lower levels of temperature and humidity.

Procedure for conditioning test specimens can call for the following periods in a standard laboratory atmosphere [50 ± 2% relative humidity, 73.4 ± 1.8°F (23 ± 1°C): Adequate air circulation around all specimens must be provided. The reason for this test is due to the fact the temperature and moisture content of plastics affects different properties such as the physical and electrical properties. In order to get comparable test results at different times and in different laboratories a standard has been established.

Harmful Component

Review in Chapter 2, **WEATHERING/ ENVIRONMENT, Weather Resistance**.

Environmental Stress Cracking

This test was prepared and is limited to type 1 (low-density) polyethylenes. Specimens are annealed in water or steam at 212°F (100°C) for 1 h and then equilibrated at room temperature for 5–24 h. After conditioning the specimens are nicked according to directions given. The specimens are bent into a U shape in a brass channel and inserted into a test tube that is then filled with fresh reagent (Igepal). The tube is stoppered with an aluminum-covered cork and placed in a constant temperature bath at 122°F (50°C).

These specimens are inspected periodically and any visible crack is considered a failure. The duration of the test is reported along with the percentage of failures. The cracking obtained in this test is indicative of what may be expected from a wide variety of stress-cracking agents. The information cannot be translated directly into end-use service prediction, but serves to rank various types and grades of polyethylene categories of resistance to environmental stress cracking. Though restricted to type 1 polyethylene, this test can be used on high and medium density PE materials as well as other plastics, in which case it would be considered a modified test.

Fire

Flammability

Underwriters' Laboratories (UL) Test 94 can be used. The placement of the specimen, the size of the flame, and its position and location with respect to the specimen are described in detail in this important UL specifications. Depending on their nonburning to burning capabilities, results of tests are reported as being materials classed 94V-0, 94V-1, 94V-2, 94-5V, etc. (Chapter 2, **HIGH TEMPERATURE, Flammability**).

Oxygen Index

The test method describes a procedure for measuring the minimum concentration of oxygen in a flowing mixture of oxygen and nitrogen that will support glowing combustion of plastics. The oxygen index is the minimum concentration of oxygen expressed as a volume percent in a mixture of oxygen and nitrogen that will just support glowing combustion of a material initially at room temperature under the conditions of this method. From this description, it is apparent that the lower the oxygen index the more the plastic contributes to the support of combustion.

Many of the basic plastics require additives that will improve their resistance to supporting combustion. These improvements vary in degree, and the designer must be cautioned not to over specify the requirement for

flammability. It should be recognized that the highest protection against burning can be costly, can contribute to higher specific gravity, and can adversely affect mechanical properties.

Analyzing Testing and Quality Control

Designers and processors should keep quality under control and demand consistent materials that can be used with minimum of uncertainty. Basically involves inspection and testing of raw materials to the finished products. Plant QC is as important to the end result as selecting the best processing and control conditions with the correct grade of plastic, in terms of both properties and appearance. After the correct plastic has been chosen, any blending, reprocessing, and storage stages of operation need to be frequently or continuously updated. The processor should set up specific measurements of quality to prevent substandard products reaching the customer. QC involve those quality assurance actions which provide a means to control, measure, and establish requirements of the characteristics of plastic materials, processes, and products.

From a practical aspect, when the expression "quality control" is use, we tend to think in terms of a good or excellent product. In industry, it is one that fulfills customer's expectations. These expectations or standards of performance are based on the intended use and selling price of the product. Control is the process of regulating or directing an activity to verify its conformance to a standard/specification and to take corrective action if required. Therefore QC is the regulatory testing process for those activities that measure a product's performance, compare that performance with established standards/specifications, and pursue corrective action regardless of where those activities occur.

There are three phases in the evolution of most QC systems; (1) defect detection where an "army" of inspectors tries to identify defects; (2) defect prevention where the process is monitored, and statistical methods are used to control process variation, enabling adjustments to the process to be made before defects are produced; and (3) total quality control where it is finally recognized that quality must extend throughout all functions and it is management's responsibility to integrate and lead the various functions towards the goals of commitment to quality and customer-first orientation (3).

When using the defect-detection approach to quality control certain problems develop. Inspection does nothing to improve the process and is not very good at sorting good-from-bad. Also, sampling plans developed to support an acceptable quality level (AQL) of 5%, for example, say that a company is content to deliver or reject 5% defects.

There are different methods to apply QC on-line. An example is with infrared measurement. The ability to record IR spectra of plastic melts provides for process monitoring and control in the manufacture process. Precise information on quality can be obtained rapidly. Furthermore, it is also possible to make measurements on unstable intermediates of importance. Although spectroscopy on melts is considerably different from that on solid materials, this does not limit the information content. IR has for many years been an important aid to investigating the chemical and physical properties of molecules. It gives qualitative and quantitative information on chemical constituents, functional groups, impurities, etc. As well as its use in studying low molecular weight compounds, it is used with equal success for characterizing plastics. It is a highly informative method of applying testing.

To ensure that QC and testing procedures are followed a quality control manual should be implemented. It is a document usually setup in a computer's software program that states and provides the details of the plant's quality objectives and how they will be implemented, documented, and followed.

Statistical Process Control and Quality Control

The term statistics basically is a summary value calculated from the observed values in

a sample or product. It is a branch of mathematics dealing with the collection, analysis, interpretation, and presentation of masses of numerical data. The word statistic has two generally accepted meanings: (1) a collection of quantitative analysis data (data collection) pertaining to any subject or group, especially when the data are systematically gathered and collated and (2) the science that deals with the collection, tabulation, analysis, interpretation, and presentation of quantitative data.

Statistical process control (SPC) is an important on-line method in real time by which a production process can be monitored and control plans can be initiated to keep quality standards within acceptable limits. Statistical quality control (SQC) provides off-line analysis of the big picture such as what was the impact of previous improvements. It is important to understand how SPC and SQC operate.

There are basically two possible approaches for real-time SPC. The first, done on-line, involves the rapid dimensional measurement of a part or a non-dimensional bulk parameter such as weight that is the more practical method. In the second approach, contrast to weight, other dimensional measurements of the precision needed for SPC are generally done off-line. Obtaining the final dimensional stability needed to measure a part may take time. As an example, amorphous injection molded plastic parts usually require at least a half-hour to stabilize.

The SPC system starts with the premise that the specifications for a product can be defined in terms of the product's (customer's) requirements, or that a product is or has been produced that will satisfy those needs. Generally a computer communicates with a series of process sensors and/or controllers that operate in individual data loops.

The computer sends set points (built on which performance characteristics of the product must have) to the process controller that constantly feeds back to the computer to signal whether or not the set of points are in fact maintained. The systems are programmed to act when key variables affecting product quality deviate beyond set limits (3).